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REMARKS ON A. S. SOKOLIK'S ARTICLE

"THE MECHANISM OF PREDETONATION ACCELERATION OF FLAMES"

By Ya. B. Zel'dovich

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REMARKS ON A. S. SOKOLIK'S ARTICLE
"THE MECHANISM OF PREDETONATION ACCELERATION OF FLAMES"

-USSR-

[Following is a translation of the article "Zamechaniya k stat'ye A. S. Sokolika 'O mekhanizme predetonatsionnogo uskoreniya plameni'" (English version above) by Ya. B. Zel'dovich in Zhurnal eksperimental'noy i teoreticheskoy fiziki (Journal of Experimental and Theoretical Physics), Vol 21, No 10, Moscow, 1951, pages 1172-1175.]

In the subject article of Prof A. S. Sokolik is considered the problem of transition of slow burning (depending on the transfer of reaction from one layer to the next by thermal conductivity and diffusion) into a detonation; that is, into a pattern of propagation of a reaction, accompanied by the formation of a shock wave with a pressure tens of times greater than that at the beginning.

The temperatures which are developed during the compression of the gas of a strong shock wave are sufficiently high to cause a fast chemical reaction in the gaseous explosive mixture; it is well known that chemical energy of explosive mixtures at a sufficiently high reaction rate is able to give rise to propagation of such a strong shock wave. Thus, the problem of the spreading of the already formed detonation wave and the problem of the origin of detonation under the influence of a strong shock wave may be considered clear, if not in all quantitative details, then in any case, from the qualitative point of view; general clarity in these problems is about 30-50 years old.

The most difficult is the problem of initial phases of transition of burning into a detonation, i.e., by what mechanism does the slow burning create a strong shock wave, and by what mechanism does the slow burning accelerate in the initial stage when the strong shock wave does not yet exist.

A. S. Sokolik thus replies to this problem:

- 1) The flame is called the source of shock waves;

2) If the burning were instantaneous, then the reaction would proceed in a stationary volume, and the pressure would increase n times; if the reaction proceeded slowly, then it would be accompanied by an expansion and there would be no increase in pressure, so that one may express the wave amplitude, by the emerging flame,

$$\Delta p = p_2 (n - 1) \frac{U_\phi}{C} \quad (4)$$

— (U_ϕ = flame velocity; C = sound velocity);

3) These elementary waves form, on the burning of every layer in sequence in the reaction zone; the flame at all times emits elementary waves, which catch up with one another and merge into one strong shock wave.

From these three premises Sokolik draws further inferences. For proof of his first premise he refers to his book (1934). There we have the description of experiments showing the origin of shock waves on flame propagation. Thus, the main point here is the acknowledgement of a fact, and not its explanation; the difference between the acknowledgement of the fact and its explanation, between the description of the phenomenon and the theory of the phenomenon, are at once apparent when Sokolik comes to the following premises and gives a formula for the pressure increase.

In reality, the propagation of pressure in the reaction zone, spreading with the given velocity U_ϕ in the explosive mixture of known properties, is well known owing to the works of our compatriot V. A. Mikhel'son and others.

From the quite indisputable equations of conservation of matter, the quantities of momentum and energy (taking into account the chemical energy of the explosive mixture), one obtains a dependence of pressure of the combustion products on flame velocity, schematically (not to scale) shown in Fig. 1.

Let us remark that all the equations, and from them the following relations between pressure and density, from which follows the curve shown in Fig. 1, are in the previously mentioned book of A. S. Sokolik (page 51, Fig. 30). As we see it, this connection does not have anything in common with formula (4) in this article. In slow burning, at a velocity (with relation to the explosive mixture) less than 50-60 meter/sec (U_{max}), the pressure does not increase, but decreases.

This lowering of pressure of the combustion products on comparison with the explosive mixture pressure in front of the flame, has been observed experimentally in a burning (of gases) in a Bunsen burner. Why then, in practice, in burning in tubes one observes the formation of shock waves; in what sense is the flame called the source of shock waves?

In slow burning in the reaction zone, at first with small

pressure increase, there follows an appreciable increase of specific volume of combustion products by comparison with the specific volume of the explosive mixture before burning. On burning, the velocity of motion of matter varies (from the explosive mixture to combustion products) and its increase is equal to $(n-1)U_0$ directed in the direction opposite to that of propagation of flames. The explosive mixture directly in front of the flame and the combustion products cannot simultaneously come to rest. The shock wave, appearing on burning, depends on motion of the system and on the mechanism of removal of combustion products.

The calculation of pressure of the shock wave necessitates the calculation of all movement, taking into account the boundary conditions.

If burning with a velocity of $U = U_2$ takes place in an open tube and at its open end the pressure is p_2 , less than p_1 , and the corresponding velocity of burning is U_2 (Fig. 1), then the pressure propagation is achieved (Fig. 2, a), the products of combustion freely escape, and the flame does not form any shock wave.

If the tube is open and the pressure at its open end is p_1 , then through the explosive mixture shall travel a shock wave having a small amplitude, with pressure (Fig. 2, b)

$$p_3 = p_1 + (p_1 - p_2) = p_1 + \rho_1 U_2 (n-1)$$

(with $U_2 = 3$ meter/sec; $n = 10$;
 $p_3 - p_1 = 0.001$ atmosphere).

If the tube is closed at the ignition end, then the boundary conditions are such that the combustion products are at rest; consequently, the explosive mixture must move with a velocity $U_2(n-1)$, for which it is inevitable that a shock wave spreads in the mixture with a pressure (Fig. 2, b)

$$p_4 = p_1 + \rho_1 U_2 (n-1) C.$$

With $n = 10$, $U_2 = 3$ meter/sec, $p_4 - p_1 = 0.1$ atmosphere, the increase in temperature in the shock wave is 80°C . In the explosion products, pressure p_5 is slightly smaller than p_4 , about 0.001 atmosphere (but higher than p_1). Thus, formation of shock waves by a flame may not be imagined to be the same as their formation in



Figure 1
 (A = U_{max})

the front, in the reaction zone, and it obviously depends on the motion of combustion products. Especially should it be emphasized that if the burning rate is constant, then only one shock wave is obtained of constant amplitude which does not radiate forced shock waves.

If the combustion rate depends on the initial temperature and the pressure of the explosive mixture, then instantaneously is established a motion pattern corresponding somewhat to the raised temperature in advance of the wave front.

In the case of our numerical example, if one should assume that the rate of combustion propagation is equal to 3 meter/sec for the initial temperature $T = 300^\circ\text{K}$ (Kelvin) and is proportional to T^2 , on solving the equation we shall find that in advance of the wave front the velocity of burning propagation is 3.18 meter/sec and the temperature is 309°K .

The accomplishment of the above verification represents the present-day investigations of theoretical research on gas motion in flame propagation. Naturally, these investigations do not negate flame acceleration and the transformation of combustion into a detonation, and do not contradict the experimentally established fact of flame acceleration and pressure increase in front of the flame.

From the synthesis of these current investigations on gas dynamics with experimental facts, it follows that the cause for flame acceleration and pressure increase may not be irradiation of shock waves by a flame in the manner described by Sokolik, and the reason may not be the influence of temperature and pressure on the flame velocity.

As is known, the way out of this difficulty was shown by Prof K. I. Shchelkin, who explained flame acceleration by the influence of gas motion on combustion propagation velocity. It would be out of place here to go again into the details of Shchelkin's theory and some complementary deliberation by the author of this article on the question of the origin of detonation.

The above stated elementary considerations show that in reality Sokolik failed to construct a new, valid physical picture of flame acceleration and increase in amplitude of a shock wave different from that of Shchelkin. Therefore, the problems raised on the influence of many factors on the origin of detonations must be solved on the basis of Shchelkin's representation, accepting them in a broad concept as the influence of gas motion on its combustion, and developing them quantitatively. Particularly, while investigating a different problem on the origin of detonation in an open tube, it is necessary to observe at great length the condition of gas outflow through the open end.

In the second part of his work, Sokolik notes that the velocity of flames in the predetonation period is equal to the bulk velocity of the gas.

city of the mass in the shock wave and there argues that "propagation of flames in the predetonation period is done by the flame transfer by bulk flow."

The velocity of bulk flow, Sokolik calculates not for that shock wave which actually exists during the predetonation period and which up till now has not been measured nor computed, and not for that shock wave which according to detonation theory ignites the gas in the formed detonation region, but for that conditional, fictitious wave, which would spread in the explosive mixture if the pressure in the shock wave were equal to the pressure of the detonation products.

In itself, the approximate equality of two quantities, the flame velocity in the predetonation period and the bulk velocity in such conditional wave, according to the magnitude order, naturally represents itself as an interesting and useful correlation.

But the arguments of Sokolik about the mechanism of the phenomenon are quite unacceptable; if one agrees with his viewpoint that, for example, the photographically observed velocity of the flames is equal to the bulk flow velocity, then it follows logically that relative to the flow, the flame remains stationary; hence, during the predetonation period new parts of the gas do not undergo combustion, so chemical energy is not liberated and there is no combustion as long as flame is carried passively by the gas. It is obvious that such a picture does not at all correspond to reality, because no quantitative evidence (considering, in addition, the mention made of which wave the calculations of Sokolik are applicable) supports his hypothesis.

In connection with the problem of amplitude of a shock wave on detonation, I mention that the presentation about a wave of equal pressure was used by Sokolik as early as 1937, and during that time when the present theory of the author was not yet constructed, such a representation was natural.

In the author's theoretical work published in 1940, it was shown that, in reality, on detonation a shock wave is formed of equal pressure, corresponding approximately to twice the pressure of the products of the explosion. If Sokolik does not agree with these assertions and at the present time stands on his previous viewpoint, then in any case he should think in detail of that problem, to take notice of the presence of the other point of view (the author's), and to show its falsity.

Sokolik uses quantities calculated on the basis of previous representations, giving good quantitative evidence, but he does not mention the existence of other representations leading to a greater (approximately 1.4-1.5 times) bulk flow velocity, that is, to a flame velocity not equal to, but smaller than, the bulk flow velocity. Such an account may disorient the reader who is not cautious enough and not sufficiently acquainted with the literature. I take this

opportunity to thank Prof Sokolik for kindly affording me the opportunity of detailed acquaintanceship with his work prior to its publication.

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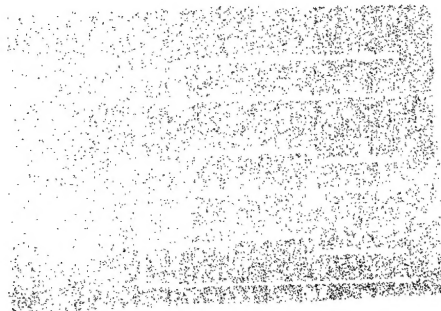


Fig. 2

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